

# The challenge of hybridization

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## Abstract

Hybridization of pixel detector systems has to satisfy tight requirements: high yield, long term reliability, mechanical stability, thermal compliance and robustness have to go together with low passive mass added to the system, radiation hardness, flexibility in the technology end eventually low cost. The current technologies for the interconnection of the front-end chips and the sensor are reviewed and compared, together with the solutions for the interface to the far-end electronics.

*Key words:* Hybridization; bump bonding; Silicon detector; pixel

## 1 Introduction

Moving from a detector prototype to a full scale system, integrated in a large experimental facility, requires a full production chain optimization where hybridization plays a crucial role. As a case study, the pixel detector for the DELPHI experiment at LEP may be considered (1). As an upgrade of the existing Silicon strip vertex detector, pixel sensor endcaps were installed, covering the low polar angle region ( $10 - 25^\circ$ ) and improving the hermeticity (2). The detector was installed in 1996 and it has been running for  $\approx 8$  months a year since 1997 without hardware interventions or dismantling, achieving the design performances. The DELPHI pixel detector represents a successful pioneering project; nevertheless, it appears

as being simple compared to the next generation of detectors planned for the future experiments at the Large Hadron Collider at CERN and the Tevatron at Fermilab (3; 4; 5; 6):

- the DELPHI detector is made up of 152 modules, for  $\approx 1.2 \times 10^6$  pixels. In the future detectors, the number of modules increases by a factor 20 and the number of pixels by two orders of magnitude.
- DELPHI pixels were meant for tracking in a low redundancy region rather than vertexing. This is the reason for the pixel cell size to be  $330 \times 330 \mu\text{m}^2$  in DELPHI, scaled down to a  $50 \mu\text{m}$  minimal pitch and area  $\approx 10^{-4} \text{cm}^2$  in the future applications where vertexing is a must. For the same region, the material budget at LHC and Tevatron is quite tight. At the

moment, the sensor and front end chip assembly, the substrate for the power bus and control lines and the mechanical support contribute to the passive material (in radiation length) according to the ratio 1 : 0.4 : 1.5. If the mechanics is still dominating, the bus substrate is far from being negligible.

- LEP is a radiation soft environment and levels below 1 Krad/year are measured. At LHC, the dose is expected to increase by three orders of magnitude, for an equivalent flux of 1 Mev energy neutrons  $\approx 10^{14}\text{cm}^{-2}$  per year at the vertex detector radii. As a consequence, all of the hybridization and assembly technologies have to be qualified as radiation hard. Moreover, while the DELPHI pixels are operated at room temperature, the future detectors will run at around  $-10\text{ }^{\circ}\text{C}$  and effects related to mismatches among the coefficients of thermal expansion of the assembly are critical.
- the DELPHI pixels are clocked at 5MHz while the future experiments requires a 40MHz clock, so that the properties of the stripline transmission lines have to be qualified.

Irrespective of the rather soft boundary conditions outlined above, the final production yield of the DELPHI pixels was at the 40% level (7). In particular, bump bonding and assembly were rather critical, with efficiencies at the 80% and 55% respectively. The future pixel detectors have a 70% production yield benchmark and much more critical constraints; achieving it without de-

grading the expected performances and fitting the time scale is the real challenge of hybridization.

In the following, bump bonding issues and techniques for the signal and power line routings are reviewed, outlining the main advantages and disadvantages.

## 2 Front-end chip and sensor interconnection

Due to the contact density ( $5000 - 10000\text{cm}^{-2}$ ), minimum pitch ( $50\mu\text{m}$ ), and the required single bump failure rate ( $< 10^{-4}$ ) the only interconnection technique is bump bonding of flipped chips. Stencil printing of conductive glue has been proven to work at larger pitch (8); anisotropic conductive film is also used by industry at larger pitches, especially for LCD packaging; stud bonding may be considered for prototyping as single dies can be bonded but it is not an option by now for a batch production.

The choice of the metal bump, whether it is going to be Indium or a solder paste, determines the process characteristics in terms of the under bump metallization (UBM), the bonding mechanism and parameters, the mechanical properties and the bump aspect ratio.

## 2.1 Solder bumps

Solder bumps have been introduced about 30 years ago by IBM to overcome the limits of wire bonding. The steps of the original IBM C4 process (Controlled Collapse Chip Connection (9)) may be summarized as follows:

- after the wafer is cleaned, the under bump metal layers are grown on the final pad by evaporation through a molybdenum mask, with ultimate via size of  $50\mu\text{m}$ . The UBM is meant to provide:
  - an adhesion layer ("active metal", usually Cr or Ti:W) on top of the final metal pad
  - a barrier layer (phased Cr-Cu) to prevent the solder dissolving the active metal
  - a solder wettable layer (Cu or Ni)
  - an oxide prevention layer (Au)
- a lead rich solder (either 97Pb/Sn or 95Pb/Sn) is evaporated through the mask, for bumps diameter and height in the  $100 - 125\mu\text{m}$  range
- the wafer is heated up to the phase transition temperature, that depends on the solder composition and may achieve a maximum of  $\approx 350^\circ\text{C}$  ("reflow"). Because of surface tension, the bump will undergo a predictable collapse to an equilibrium shape corresponding to a truncated sphere (10). Reflow may occur in presence of a suitable flux or in an organic compound bath.

The original IBM prescription presents three major limitations (11; 12; 13): because of the mismatch between

the Silicon and Molybdenum coefficients of thermal expansion the process cannot be effectively scaled up past 5 inch wafers; the finite mask thickness and the mask alignment procedure limits the typical pitch to  $250\mu\text{m}$ ; eutectic Pb/Sn solder cannot be evaporated due to the low vapour pressure of the Sn. The use of eutectic solder bumps (37Pb/Sn, with a reflow temperature of  $230^\circ\text{C}$ ) is pursued by industry as it provides the option of mounting the IC onto the circuit board using the same techniques employed for the surface mountable components. These limitations are currently overcome by electroplating the UBM and the solder in a pattern defined by photore sist masks (13; 14). Critical parameters in this case are solder height and alloy uniformity, linked to the control of the plating current and solution flow; solder voiding has also been reported (12; 13), connected to hydrogen entrapment in the plating solution. Industrial standards correspond to  $150\mu\text{m}$  pitch for  $70 - 80\mu\text{m}$  footprint.

Surface tension effects during the reflow are essential during the flip-chip attachment, as they induce self-alignment and planarization of the chip with respect to the substrate (15). As a consequence, effective bonding is achieved for overlaps between the bond and the wettable substrate pad exceeding 25% of the pad area.

The main issues making the solder bump techniques appealing for the interconnection of sensors and front-end chips are: bump uniformity and

self-alignment properties, resulting in a low single bump failure rate; the optimal height/pitch ratio, e.g.  $15 - 20\mu\text{m}$  height for a  $50\mu\text{m}$  pitch (16; 17), limiting the parasitic capacitance also in a single sided process; the excellent electrical properties (contact resistance at the  $\text{m}\Omega$  level (17)). On the other hand, there are critical issues that should not be underestimated as they could affect the interconnection reliability: the UBM is quite complex and a not perfect control of the metallurgy can result in a poor adhesion; the process requires relatively high temperature steps, that might not be tolerated by radiation hard processes; the reflow chemistry should guarantee wire bondability of the I/O pads. Thermal fatigue and high stress induced by mismatches in the coefficient of thermal expansions of the assembly are also of concern (18; 19); the mechanical properties (in terms of ultimate tensile and shear stress) depends on the bump dimensions, on the UBM characteristics and the substrate material but in general fatigue life is increased by the use of a filler between the substrate and the chip (12), possibly not tolerated in assembling detectors. In current high energy physics applications, up to 16 chips are connected to same substrate; replacing a faulty chip ("reworking") could considerably improve the yield. For instance, in the DELPHI pixel detector the module production yield after bump bonding of 16 known good chips was 80% and a good part of the faults were on a single chip. Reworking chips as close as  $50\mu\text{m}$  is not trivial in term of the required temperature and stress and

mostly because residual solder has to be cleaned before the new placement occurs.

Nevertheless, excellent results were obtained on small volume detector assemblies for the WA97 (20) and DELPHI experiments (2) and on prototypes for the ATLAS experiment (21), with single bump failure rate in the  $10^{-4} - 10^{-5}$  range and pitch down to  $50\mu\text{m}$ . The results obtained so far proves the technology is mature and solutions to specific problems certainly benefits of the enormous knowledge gained to define an industrial standard.

## 2.2 Indium bumps

Indium bumping technology has been developed for Infrared Sensor assemblies as In retains its mechanical properties also at liquid Nitrogen temperature where the sensors are operated. In bumps are in general grown by evaporation through a patterned photoresist, after a proper UBM. The UBM may be simple and limited to a single Cr adhesion layer and bump pitches in the  $20 - 30\mu\text{m}$  are standard (22). Chemical etching of the photoresist and evaporation are critical parameters in the process, as a bad control may result in Indium attachment to the via walls, making the lift-off not effective (11; 22). As a result of it, In bumps have a small height/pitch ratio (e.g.  $7\mu\text{m}/50\mu\text{m}$ ) and bumping on both sides of the dies being assembled may be necessary (23). Indium belongs to the third group

of the periodic table and it features a remarkable tendency to form an oxide crust (its electrode potential is +0.38 V, to be compared to +1.66 V for Al). As a result of it, bump reflow is extremely difficult even if possible according to proprietary processes (see for instance (24)). Solid state diffusion bonding occurs at moderate pressure ( $10^{-2}$ N/bump) and temperature (20 – 100°C) (22; 23), but it requires excellent planarity (at the 0.1mrad level) and bump uniformity. The latter is the most critical point of the In bumping technology, together with a possible electronics noise increase due to the "small" bumps. The remarkable points may be summarized in the simple UBM, the low bonding temperature and the fact that industry standards match the requirements for detector assembly. Reworking appears simpler as the In left over on the substrate may be used for the fresh substrate attachment. Indium plastic properties should help in system assembly but this has to be traded off with a lower shear and tensile strength with respect to solder bumps. The ultimate tensile strength for SnPb bumps has been measured to be in the 25 – 50MPa range (18), to be compared to 1.9MPa for In at room temperature (25); the ultimate shear stress for solder bumps is in the 25-40 MPa range, while for In is 6.1 MPa.

Excellent results on detector assemblies have been obtained on prototypes for the ATLAS and CMS pixel detectors and have been reported at this conference (23; 24; 26); the single bump failure has been measured to be at  $10^{-5}$  level and the system re-

liability is under investigation.

### 2.3 Conclusion

Flip chip technologies based on both solder and Indium bumps have been proven to be a solution for detector assembly. The statistical single bump failure rate is well within the specifications. The choice between either of the two technologies will possibly be defined by the long term reliability, the thermal compliancy of the assemblies and by the quality of the process control, i.e. by its repeatability.

## 3 Power lines and signal bus

After the front-end chips are bump bonded, the assembly of a module is completed routing the power and digital lines, housing the controller chip and eventually temperature sensors and the opto-package for the interface to the far-end electronics. This may be accomplished by two different approaches:

- the "flex" hybrid technology, where routing is defined in a multilayer polyimide film glued on the substrate. The passive components are connected with standard surface mount technology and wire bonds interconnect the traces to the I/O pads of the front-end chips. The controller chip may be connected either by wire bonds or flip chip. This approach was used in DELPHI (1) and it is considered the baseline option for the pixel

detectors at the LHC experiments and BTeV, reporting the latest developments at this conference (4; 27; 28)

- the Multi Chip Module with Deposited Dielectric (MCM-D) technology, a robust and monolithic approach based on thin film technology (17). In MCM-D, routing is again defined in a multilayer film but grown on the substrate, where the dielectric is deposited by spin coating and the traces are electroplated. Passive components may be integrated in thin film technology and the chip I/O pads are interconnected by bump bonding. This approach is being developed for the ATLAS pixel detector; the basic principles and the latest developments have also been reported at this conference (29).

The two solutions are similar as far as the passive material added to the system ( $\approx 0.1\% X_0$  (30)) and opposite in any other respect. Flex hybrids are a mature industrial technology and the requirements for the generic detector assembly fit the standards. Wire bonding reliability is a concern but it is not expected to be critical. The main issue is the very large mismatch between the coefficients of thermal expansion of flex ( $\approx 45 \times 10^{-6} \text{ }^{\circ}\text{C}^{-1}$ ) and Silicon ( $2.5 \times 10^{-6} \text{ }^{\circ}\text{C}^{-1}$ ) that can induce a severe stress on the bumps moving from the assembly to the operating temperatures, i.e. from  $20^{\circ}\text{C}$  to  $\approx -10^{\circ}\text{C}$  (26). The MCM-D technology offers the advantages and disadvantages of a monolithic approach. On one hand, no wire bonds are foreseen and the assembly scheme min-

imizes the stress on the bumps, as the multilayer is to be grown on the junction side of the sensor. On the other hand, the requirements on the single bump failure rates are tighter, as the front-end I/O pad are also bump bonded; moreover, each sensor cell is connected to the mating electronics cell by a staircase of feed through connections also requiring a high quality assurance. Last but not least, the MCM-D is necessarily tested after being grown on the sensor substrate so the possibility to rework the substrate in case of failure is a must in terms of yield optimization. The current results demonstrate the integrated solution is certainly appealing but the process optimization is still under way, both in industrial applications and in detector assembly.

## 4 Conclusions

The next generation of pixel detector trackers represents a real challenge as every system characteristics is at the edge of the current technology. Moreover, the total area is such that the proposed solutions have also to guarantee a high production yield. Hybridization is not less demanding: suitable technologies exist and quality assessment is on the way, with a full qualification by the production starting soon.

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